Parametric Radar Cross-Section Study of a Ground Combat Vehicle

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Abstract A computer geometry model of the ZSU-23-4, quad 23-mm self-propelled anti-aircraft gun was obtained in BRL-CAD, a combinatorial solid-geometry-based modeling system. The BRL-CAD file served as input to a software package (ECLECTIC) that generated a flat, triangular, all-metal facet representation of the ZSU-23-4 exterior structure containing approximately 78,000 facets. The facet model served as input to Xpatch, a high-frequency signature prediction code based on the shooting and bouncing ray (SBR) technique. Xpatch was run at the DoD Army Research Laboratory (ARL) Major Shared Resource Center (MSRC) on the SGI O2000 high-performance computers. The configuration parameters for the ZSU-23-4 model, both with and without a perfect metal ground plane, included two depression angles (12° and 30°), both polarizations, 256 frequencies (about each center frequency), and azimuth steps of 0.05° (for *X*-band) and 0.015° (for K_a-band). The configuration parameters were selected based on radar measurement data taken on a ZSU vehicle at the ARL Aberdeen field test facility. The model predictions include radar cross-section data as a function of polarization and angle, and synthetic aperture radar (SAR) images. We detail the modeling efforts involved in the largest and most computationally intensive configuration in the program.

INTRODUCTION

The Army Research Laboratory (ARL) is participating in a North Atlantic Treaty Organization (NATO) research study group (RSG20), with a focus on the military applications of millimeter-wave (MMW) imaging. RSG20 conducted an experiment at Swynnerton, UK, involving the use of airborne synthetic aperture radar (SAR) systems to collect imagery of a military location. The experiment assessed the applicability of MMW imaging for locating and engaging ground vehicles and other fixed targets. One of the ground vehicles used in this test was a ZSU-23-4 (see Figure 1), a quad 23-mm self-propelled anti-aircraft weapon system. ARL conducted a series of measurements at the outdoor signature research facility at ARL Aberdeen Proving Ground (ARL-APG), MD, in August of 1996, to characterize the MMW signature of this vehicle for comparison to similar measurements obtained at Swynnerton. As an adjunct to the original intent of comparing measurements, the participants agreed to perform radar cross- section (RCS) predictive modeling using this target as a baseline. The U.S. agreed to provide a flat, triangular facet representation of the exterior structure of the ZSU suitable for RCS calculations. The parameters used in the modeling would be the same as those used in the measurements by ARL. The aim was to allow direct comparison of model results with a standard set of signature visualization tools[1].

The fully polarimetric instrumentation radars at the ARL-APG signature research facility were used to collect data on the ZSU vehicle at *X*-band, K_a-band, and *W*-band.

Table 1 summarizes the main characteristics of the measurement instrumentation, shown in Figure 2. A full description of the operation of the radar and data acquisition system can be found in reference 2. Measurements made with this system are taken with the radar mounted on an elevator on a 125-ft tower. The radar is pointed at an in-ground turntable 153 ft away. The test vehicle sits on this turntable. Target rotation is always counterclockwise; thus, 90 degrees is always on the left side of the vehicle when one looks at it head-on. A complete rotation for frequency measurements at 34 GHz takes about 10 min. A fully calibrated RCS plot can be ready in 10 min after the measurement is completed. A series of ISAR images displayed on a CRT as a movie is available 25 min after each measurement is completed. Table 2 displays the measurement conditions that were replicated in the ZSU modeling work.

DEVELOPMENT OF THE FACET MODEL

The computer modeling of the ZSU-23-4 begins with the development of a geometric representation of the exterior of the vehicle in some suitable format. An existing geometry model of the ZSU was found at ARL-APG. This geometry model was created with the Ballistic Research Laboratory–Computer Aided Design (BRL-CAD) software package. These types of models were developed to analyze various physical properties (such as center of mass and moments of inertia), vulnerability, and, in recent years, for optical, radar, and IR signatures.

BRL-CAD software development started in 1979 to provide an interactive graphics editor for the BRL vehicle description database. The software package includes a solid geometric editor, the ray tracing library, different lighting models, and many image handling, data comparison, and other supporting utilities. This software package now totals more than 500,000 lines of C source code and undergoes continuous development (the current version number is 4.4). It runs under UNIX and is supported by more than a dozen product lines, from Sun workstations to SGI supercomputers. BRL-CAD supports a variety of geometric representations, including an extensive set of traditional combinatorial solid geometry (CSG) primitive solids, such as blocks, cones, and torii: solids made from closed collections of uniform B-spline surfaces as well as nonuniform rational B-spline (NURBS) surfaces: purely faceted geometry: and n-manifold geometry (NMG). All these geometric objects may be combined using Boolean set theory operations, such as union, intersection, and subtraction. All the geometric entities provide for different material representations. The software is an unpublished work that is not available to the public, except through the terms of a limited distribution agreement. BRL-CAD is licensed at 800 sites worldwide.

The BRL-CAD representation of the ZSU vehicle contains both interior and exterior feature details. This representation is not suitable as input to the software selected to perform the RCS calculations (Xpatch). This software requires a triangular facet representation or an international graphics exchange specification (IGES) representation of the exterior structure of the vehicle. At least two geometry format conversion packages are available that accept a BRL-CAD input file and produce facet and/or IGES formats. In addition, Xpatch software includes a utility that performs this conversion. A decision was made to generate a facet representation of the model, since Xpatch can compute the required data about four times faster from a facet input file than from an equivalent IGES input file. The speed difference is related to the ray-tracing algorithm in the software.

Initially, a utility in Xpatch (called Cifer) was meant to convert the BRL-CAD file into a facet representation. This attempt failed because the ZSU CAD representation was too large for processing in a single step. It would have been necessary to edit the CAD model (with BRL-CAD) to divide the original model into three or four segments, facetize each segment, and recombine the faceted segments. The next attempt employed a software converter (named ECLECTIC—a prerelease version) that was developed by the Army Tank and Automotive Command (TACOM). ECLECTIC is an extension of an earlier converter, called Facet Region Editor (FRED), which was also developed at TACOM to generate flat, triangular facet representations from BRL-CAD geometry models to support infrared (IR) analysis on computers. ECLECTIC generates facet models in several stages, identifying and facetizing geometry primitives, separately handling intersections of primitives (edges), and determining interior and exterior elements of the model. Several levels of facet size refinement are available in the code, from coarse to relatively fine (designated 1 to 10 respectively). It was planned to examine the ZSU model at several different facet sizes to compare the resulting representations for quality (facet skewness), uniformity and number of facets. However, the need for an unexpected early release of the model to the NATO participants forced the use of the facet representation existing at that time. The model facet level used in this program was four, slightly higher than the default value in the software. It seems appropriate to comment here that even if the facet level in the software were set to the highest level (i.e., 10), the facet model would still consist of the same order of magnitude of individual facets. The conversion software employed here cannot produce the "high-resolution" facet model of the ZSU discussed later in this paper.

The ZSU facet model used in this work consisted of a flat, triangular facet representation of the exterior structure of the vehicle. The model contained 40,037 nodes and 77,955 facets, with each facet representing metal material. This number of facets and the lack of overall consistency in size and uniformity of the individual facets categorize the model as a "coarse" representation. The use of flat, triangular facets to represent curved features on the ZSU model always results in some error. Ideally, the facet size should be determined by the frequency at which the model is expected to produce results. The general guidance in low-frequency codes is that each surface polygon be no wider than one-fifth of one wavelength of the radar signal. This rule would be required for accurate representation of small, curved surface features on the vehicle. For the flat portions, tessellation size is mostly irrelevant. These requirements on facet size at high-frequency relegate the design of high-resolution facet models to professional model developers. One result of not adhering to these modeling guidelines is that the predicted signatures tend to have more sharp peaks due to specular reflection, which would be greatly reduced by a curved surface representation.

The following illustrations present the facet model as it would have appeared to the ARL-APG radar on the boresight axis (but larger in size). The first two figures

(Figures 3 a,b) depict a depression angle of 30 degrees, with the azimuth angle as indicated on the figures. The next two figures (Figures 3 c,d) depict a depression angle of 12 degrees, with the azimuth angle as indicated on the figures.

Xpatch SOFTWARE

The first version of Xpatch was developed in 1988 at the University of Illinois in Urbana-Champaign. The code remained largely unused for several years. In late 1991, the code was adopted as a signature computation tool by the Air Force. Xpatch currently enjoys DoD support for feature enhancement and distribution under the software development activity that is part of the Defense High-Performance Computer Modernization Program (HPCMP). One goal of this activity is the porting of Xpatch software to all parallel computer architectures in the program. SAIC-DEMACO, Inc., and the Center for Computational Electromagnetics at the University of Illinois are responsible for current development of the software. The latest version of the software (version 2.4d, released March 1997) is supported on most SGI and SUN computer platforms.

Xpatch is a high-frequency radar signature prediction code based on the shooting and bouncing ray (SBR) technique. In SBR, a dense grid of rays is shot from the radar direction toward the target. Rays are traced according to geometrical optics theory as they bounce around within the target. The tracing includes the effects of polarization, ray divergence, and layered material transmission and/or reflection. At the point where the ray exits the target, a physical optics integration is performed to calculate the scattered far field from the target. All single- and multiple-bounce contributions are included in the geometrical or physical optics theory. Current versions of Xpatch allow for first-order edge diffraction to be included in the computations. This software consists of three parts: (a) electromagnetics: XpatchF, and XpatchT for frequency-domain and time-domain calculations, (b) CAD and visualization tools, and (c) a graphical user interface (GUI). The code is written in FORTRAN, C, and C++ languages. The electromagnetic (EM) portion and the ray tracer consist of approximately 0.6 million lines of code, and the tools and GUI account for 0.8 million lines of code. Table 3 describes some of the differences between the two EM domain computations in Xpatch. The distribution of the Xpatch computer code and its documentation is subject to export control laws. The code is generally available to U.S. Government agencies and contractors performing work for the Government.

The accuracy of Xpatch for RCS calculations depends on many factors, one of which is the facetization representation of the model. One concern is that extremely narrow facets generate numerical instabilities in the Xpatch ray tracer. The actual criterion used to disqualify a facet is a complex expression in geometrical terms. Facets with very small interior angles (less than 0.002 degrees) and side ratios in excess of 10 to 1 have a good chance of being rejected by the code. A utility in Cifer checks and reports "bad" facets in the facet model. There were three "bad" facets identified in the current ZSU model. These facets are simply ignored by the code. Any rays that intersect these facets disappear into the interior of the model and are not accounted for in the far-field determinations. The size and locations of the “bad” facets were such that they were judged to be insignificant for the accuracy of the calculations performed in this work. Other issues related to facetization, such as verification of a closed, connected, continuous outer surface (except for the three bad facets) were checked with other Cifer utilities.

There are significant concerns about Xpatch software when considerations of verification arise for cases in the higher frequency ranges of 35 and 95 GHz. Xpatch was originally designed for the *X*-band frequency range, hence the name “X” patch. While the software is increasingly being applied at the higher frequency ranges, there does not exist a significant body of verified data to warrant putting a high confidence level in the results.

The current versions of Xpatch have known limitations that can cause measurable errors if they are not considered in the interpretation of the computer results. For instance, the existence of cavities and large seams in the object cannot be treated in the present versions of the code. Therefore, little confidence can be placed in results at very low depression angles, where the wheels/tracks of the vehicle are illuminated and would form a set of large cavities. In addition, there is no present capability to consider the effects of surface roughness on the vehicle. Finally, while there is a provision to incorporate material properties in Xpatch as part of the model, layered materials and uncertainty in material properties require experience in the interpretation of Xpatch data.

COMPUTING TECHNIQUE FOR 1999 STUDY

The ZSU configuration for radar excitation at a 30º elevation angle over a metal ground plane (see Figure 4) required the most extensive computational resources in the program. A complete set of RCS data involved both polarizations, a full 360° azimuth sweep at steps of 0.015°, with 256 frequencies centered at K_a-band. Xpatch software was installed on each of the SGI-Origin O2000 platforms (four machines). The problem was divided into 24,000 jobs (one for each azimuth angle step) that could be run in parallel and unattended on the SGI platforms. A set of UNIX scripts generated and controlled the execution of each job, monitored the number of jobs waiting on the machines, and submitted 40 jobs for execution whenever fewer than 10 jobs were in the queue. This configuration generated over 3 GB of data and took about four months to complete.

The executions were distributed across four SGI Origin systems, representing three generations of the MIPS microprocessor family. The computations began just one week after the ARL MSRC became the first site worldwide to operate an Origin2000 with the MIPS R12000 CPU. At the time, the four machines were configured as follows:

- 32 R10000 250-MHz CPUs, 32 GB
- 64 R12000 300-MHz CPUs, 64 GB
- 64 R10000 195-MHz CPUs, 32 GB
- 128 R10000 195-MHz CPUs, 128 GB

The second 64-CPU system was upgraded to 300-MHz R12000 CPUs and 64 GB one week after the computations began, and the 128-CPU system was upgraded two weeks later. This mixture of processor types provided an opportunity to investigate the performance of the three processor types. Although the primary difference between the processors is the clock rate, there are other important differences as well. The frequency of the secondary cache is 120-, 250-, and 200-MHz on the 195-, 250-, and 300-MHz processors, respectively, and the R10000 utilizes a 4-MB cache while the R12000 uses an 8-MB cache. The R12000 also has a more extensive branch prediction (2048 entries vs. 512) capability [3].

Table 4 summarizes the average runtimes and number of cases by CPU type. As compared with the 195-MHz processors, the 250-MHz processors performed 25.5% better while the 300-MHz processors performed 46.4%. This compares well with the clock rate increases of 28.2 and 53.8%, respectively.

Another interesting feature of the measured performance data is the comparison of similar processors on systems containing 64 and 128 CPUs. The addition of the Origin2000 metarouter is required to grow a system beyond 64 CPUs. Adding the metarouter increases the average remote latency of the system from 867 to 945 ns [4]. Table 5 lists the average runtime and number of jobs by system size and processor type. With R10000 CPUs, there is a 3.5% difference between 64- and 128-CPU systems, whereas there is only a 1.6% difference with the R12000. This reduction in the penalty imposed by the metarouter is most likely due to the larger, 8-MB cache. In any case, the data show that the latency increase for these relatively small jobs is almost insignificant.

The efficient processing of the 24,000 individual jobs associated with this work required some thought. The resulting methodology met the following criteria:

- able to process jobs independently of one another
- completely automated
- able to simultaneously process as many jobs as possible, and
- friendly queuing system (not 24,000 entries in qstat).

The jobs were submitted to the queuing system via a single CRON job, a UNIX scheduling process, that created the input files and submitted 40 jobs at a time if there were fewer than 10 tasks remaining in queue-wait status. The CRON job executed every 15 min. This implementation was easily managed and functioned well.

The original allocation of approximately 30,000 hours was consumed quickly, necessitating a shift to background processing for many of the tasks. This was easily managed by changing the default project or by using queuing system utilities to change individual tasks to background. Later in the project, an additional 50,000 hours of allocation were secured, allowing the project to shift back to foreground processing. Of the 24,315 tasks, 15,407 were processed at project priority and 8,908 were processed in the background. In all, approximately 100,000 CPU hours were consumed.

DATA FORMAT AND ANALYSIS

The computed data (monostatic RCS as a function of frequency and angle) were written in ASCII format. The 24,000 files, compressed to nearly 280 MB, were written on 4-mm DAT tape and transferred to our local Octane machine for analysis. The Xpatch data were converted into the data format of the ARL-APG radar measurement system (raw) data. This allows for a direct one-for-one comparison between measurement and computed results. This direct comparison extends to the format of the data output plots and ISAR image presentations/movies, since the signal/data processing software is the same for both measured and computed data. This common processing software includes the data analysis tools developed and verified over the years at a modern, production radar measurement facility. Further, all the standard statistical parameters used to characterize the measurement data are automatically available and can be applied to the computed data. At APG, a standard format is used for all RCS polar plots, allowing the ZSU computed data to be directly compared against data from other vehicles measured at the APG facility. The Xpatch data were also plotted directly with the Matlab™ processing and visualization package as an additional check on the data conversion exercise.

While the benefits to this data conversion are evident, there were difficult challenges to overcome to fully implement this idea. Modern radars include a complex signal-processing pipeline acting on the raw data to account for many factors (including channel imbalance, image rejection, clutter elimination, etc). This signal-processing pipeline at APG uses a set of five reference/calibration files that "correct" the raw data based on reference measurements and calibration factors. The converted, computer-generated, Xpatch data must flow down this signal-processing pipeline for analysis by the APG software. Xpatch data are "perfect", since all the above corrections are not applicable, with the exception of scaling the computer data to the correct magnitude. The challenge was to generate five reference/calibration files that approximate a perfect radar system by not altering the computer data (scaling is the exception). Fortunately, with help the system designer and software developer, the needed reference/calibration files were developed.

Preliminary data analysis involved visual comparisons of RCS values versus azimuth angle for predictions and measurements. The first point noticed was that the computed data for transmit vertical/receive vertical (VV) and transmit horizontal/receive horizontal (HH) copolarizations were identical for all cases. This was also the case for the computed cross-polarization field components VH and HV. Apparently, this was a consequence of an all-metal representation for the problem, since for metal, the reflection coefficient is negative unity for both field polarizations. A comparison of measured data with computed data (using the metal ground plane configuration) revealed that the ZSU data were too large in value (in some instances more than 10 dBsm larger than the measured values), and the character of the RCS plots were visually different. The representation of the ground as a metal conductor was responsible for the discrepancy. However, for the high-frequencies involved in this work, the radar measurement data include a unique ground effect (Brewster effect) that occurs for small elevation angles and vertically polarized incident radiation. Under these conditions, the reflected wave from the ground onto the target is extremely small (almost vanishing for a unique incidence angle). The implication for the ZSU analysis is that for a 30° elevation angle with vertically transmitted polarization at both frequencies, the ZSU data without a ground plane should be used for comparison with the measurement data. This comparison produces a close overlay of the mean values of the RCS data. The predicted ZSU data still have several sharp prominent features that are not represented in the measurement data, but the intuitive perception is that the predictions are *close* to measurement. Figure 5 shows one of the better comparisons between Xpatch data and the APG measurement data for the ZSU. The data presented in this figure are the average over frequency of the RCS (in dBsm) values plotted at every 0.5° in azimuth. ISAR images (actually movies) were generated from the ZSU computed data with the APG software, but no significant analysis was performed with them. The ISAR information is much less affected by the mean value of the RCS data. Figure 6 shows a comparison of an ISAR image with measurement data.

Future Plans

The work on the ZSU to this point provides a perspective for the future effort. A long-term goal in our modeling program is to predict the ZSU signature at W-band, for comparison with measured data. A better representation for the earth ground must be included with the vehicle model. A high-resolution enhanced vehicle model is required for K_a-band and beyond. The new Common High-Performance Software Support Initiative (CHSSI) developed version of Xpatch (ver. 4.6) will be available and employed for future computation. A new Global Resource Director (GRD) task-based job processing approach and multiplatform capability recently implemented at the ARL MSRC will be heavily utilized.

Model of the Earth Ground: We can infer that the earth response is a very important contribution to the RCS for ground vehicles. The representation of the earth ground as a metal conductor led to overestimates in the predicted RCS values of the ZSU. (This had much less effect on the SAR image data.) The present version of Xpatch has the capability to model arbitrary materials by defining the permittivity and permeability material constants in the model (exactly in the frequency domain, approximately in the time domain). There is also a provision for providing the reflection coefficient (instead of the material constants) to reduce the model size and computation time for the code. A more realistic representation of the earth ground will break the redundancy of the polarization data, providing better agreement with measurement. The existence of the Brewster effect can be exploited to push the model response to *W*-band for meaningful comparison with measurement, with reasonable computational resources.

Computer Vehicle Models: The low-resolution ZSU model cannot adequately represent the scattering from curved surfaces on the target. This leads to sharp features in the RCS data, because specular reflection from large plane triangular facets is more probable than diffuse reflection from a curved surface. A high-resolution model for the ZSU (see Figure 7), constructed by professional computer-aided design technicians, has been obtained from the Army Target Management Office (TMO) at Redstone Arsenal. The model contains approximately 850,000 facets and took about 3-1/2 months to construct. It has detailed representations of smaller features than the low-resolution model, and it has a much better representation of the curved surfaces on the vehicle. As the radar frequency increases, relatively smaller features on a target can contribute substantially to the scattered field. When feature size becomes of the order of a wavelength of the illuminating field, strong interactions result. The high-resolution model will be needed to get more accurate results at K_a- and W-band. We also plan to run the high-resolution models at X-band to determine if the more accurate representation of curved surfaces on the vehicles will be observable in the RCS data.

Xpatch Software: The present version of Xpatch software distributed by Wright Laboratories to DoD is 2.4d, released in March 1997. We plan to use the beta release of the CHSSI product (version 4.6), which should be available later this year. Two improvements of direct relevance for this work include increases in processing speed (64% for the frequency domain version, 51% for the time domain version) over the present version. The new software also offers extensions and enhancements to the existing code that include near-field capabilities, multiple IGES entities, hybrid capability, and three-dimensional (3D) scattering centers [5]. The 3D scattering center extraction from a 3D ISAR image has the potential to greatly speed up the determination of RCS angular data. Most important is that since this software is a product of the CHSSI program, issues of efficiency, scalability, and optimization in the high-performance computing environment have been fully addressed.

MSRC Evolution: In January 2000, the ARL MSRC installed an updated release of GRD software, version 5.0. This new release supports the concept of jobs consisting of many independent tasks. This new feature will allow the increased resolution modeling effort to be more efficiently processed than was possible using the CRON-based script. The entire run can be contained in a single batch job that will manage all tasks. Although each task will be considered separately for scheduling and accounting purposes, the entire job can be managed through a single queuing system utility command (ex. qsub, qstat, qalter, qdel).

Another significant improvement at the ARL MSRC is the redesign of project implementations. The first three characters of the HPCMP-designated project numbers have been removed from the queuing system controls. These characters designate a system that has been allocated for the project. By eliminating these from the queue access lists, the center now allows users to submit a job without specifying the system architecture. If the user has access to more than one resource (Sun and SGI, for example), the job will be scheduled on the first available platform. Consumption of each resource is reported separately and access control lists prevent users and/or projects without allocations on a specific system from running there. These newly implemented features are expected to further improve the scheduling efficiency for the upcoming higher resolution investigation.

Conclusions

Programs to design and develop the next generation of the nation's combat systems rely heavily on modeling and simulation to provide guidance on the integration of competing, and in some cases, conflicting, requirements for performance and survivability. For the development of stealthy, survivable Army platforms that are integral assets to the Army Vision–Future Combat System, the nonballistic survivability suite of requirements now includes RCS specifications and guidelines. These new requirements extend the frequencies of concern into the MMW region of the electromagnetic spectrum, well beyond the design limits of the DoD-endorsed RCS predictive tool, Xpatch. The ZSU modeling work is providing guidance on model resolution, geometry, and physical construction features that affect the RCS of combat vehicles at frequencies well above *X*-band. Advances and developments in numerical computation software, hardware resources and control environments, and model representations are being exploited to

- help to determine criteria for radar discrimination between different systems on the battlefield (friend or foe identification),
- provide guidance for the application of Xpatch well outside its design frequency limits, and
- provide more accurate baseline system performance characterization for smart munitions development.

ARL has already made available a subset of the models and data generated in the ZSU work to the Electromagnetic Code Consortium (EMCC) for their national benchmarking program. This program is aimed at compiling a national repository of select targets, along with corresponding government data on each target, as a baseline for the evaluation of new/improved codes, or to allow contractors to test/evaluate codes that are proposed for use on government contracts.

References:

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Figure Captions:

Figure 1. ZSU-23-4 vehicle at APG measurement facility.

Figure 2. *X*-, K_a-, and *W*-band polarimetric ISAR.

Figure 3. ZSU facet model as it appears to APG radar measurement facility looking down boresight of radar. Configuration shows 30° depression angle and (a) 30° and (b) 260° azimuth angles.

Figure 3 (cont'd). ZSU facet model as it appears to APG radar measurement facility looking down boresight of radar. Configuration shows 12° depression angle and (c) 45° and (d) 225° azimuth angles.

Figure 4. "ModelMan" software (from SAIC), showing ZSU-23-4 over metal ground plane (plane size = 2200 in).

Figure 5. Comparison of Xpatch and APG RCS data for ZSU measurements at K_a-band, 30° elevation angle, copolarized field components (vertical transmit, vertical receive).

Figure 6. Comparison of Xpatch and APG ISAR data for ZSU measurements at *X*-band, 30° elevation angle, –135° azimuth angle.

Figure 7. ZSU high-fidelity virtual target model (from TMO) containing 852,803 facets.

Tables:

Table 1. *X*-, *K*-$_a$, and *W*-Band Polarimetric ISAR Instrumentation

Center frequency (GHz)	9.25	34.25	94.25
RF bandwidth (MHz)	1511.64	1511.64	1511.64
Frequency step (MHz)	5.928	5.928	5.928
Peak power (dBm)	+27	+20	+13
Pulsewidth (ns)	100	100	100
PRF (MHz)	1.0	1.0	1.0
3-dB Beamwidth (deg)	8.5	8.5	8.5
Polarization isolation (dB)	30	35	35
System noise figure (dB SSB)	7	9	11
Min. detectable signal (dBsm)	-80	-80	-80

Transmitted polarization Vertical (V) and Horizontal (H)
Received polarization V and H

Table 2. ZSU Measurement Parameters

	X-Band	K_a-Band
Nominal center frequency (GHz)	9	34
Start frequency (GHz)	8.00000	33.48836
Stop frequency (GHz)	9.51164	35.00000
Step frequency (MHz)	5.928	5.928
Number of frequencies	256	256
Depression angles (degrees)	12 and 30	12 and 30
Angle sampling interval (degrees)	0.05	0.015

Polarizations Linear: VV, VH, HV, HH

Table 3. Comparison Between XpatchF and XpatchT

Capabilities	XpatchF	XpatchT
Computation domain	Frequency	Time
Target geometry	Facet/IGES/CSG	Facet/IGES/CSG
Coatings/materials	Yes	Approximate
First bounce	PO/z-buffer/SBR	z-buffer/SBR
Higher bounce	SBR	SBR
Edge diffraction	Metal	Metal
Best for	RCS/Range-profile	SAR/range-profile

Table 4. Average CPU time and number of jobs by CPU type

CPU type	Average CPU time (s)	Number of jobs
195-MHz R10000	20,340	2,217
250-MHz R10000	16,202	3,455
300-MHz R12000	13,898	18,643

Table 5. Average CPU time and number of jobs by system size

System size and CPU type	Average CPU time (seconds)	Number of jobs
64 195-MHz R10000	19,910	849
128 195-MHz R10000	20,607	1,368
64 300-MHz R12000	13,818	11,977
128 300-MHz R12000	14,041	6,666

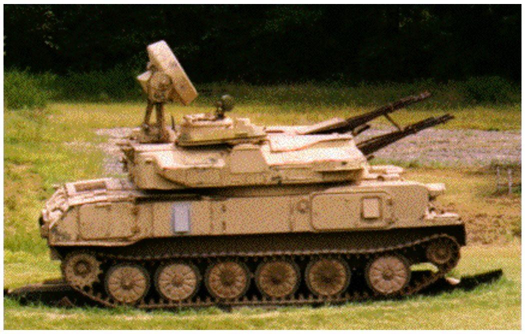

Figure 1. ZSU-23-4 vehicle at APG measurement facility.

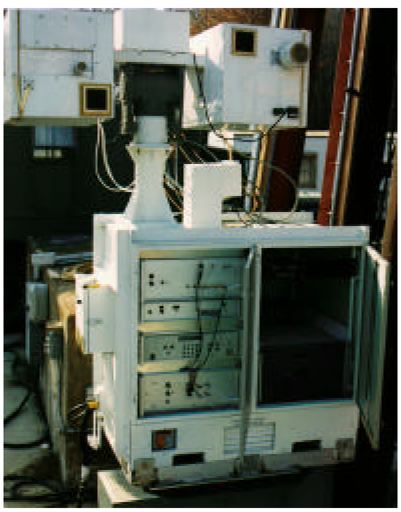

Figure 2. X-, K_a-, and W-band polarimetric ISAR.

(a) (b)

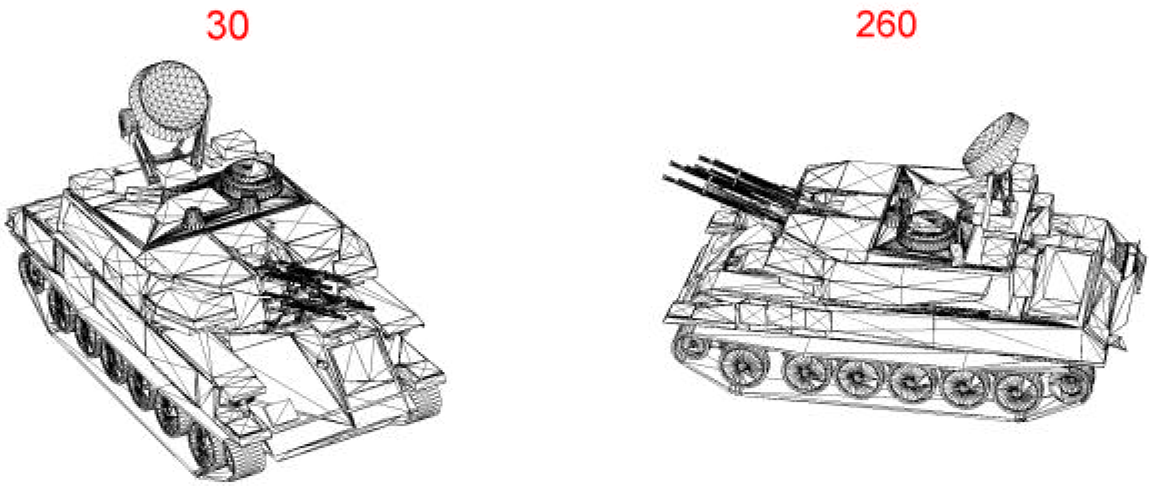

Figure 3. ZSU facet model as it appears to APG radar measurement facility looking down boresight of radar. Configuration shows 30° depression angle and (a) 30° and (b) 260° azimuth angles. Configuration shows 12° depression angle and (c) 45° and (d) 225° azimuth angles.

(c) (d)

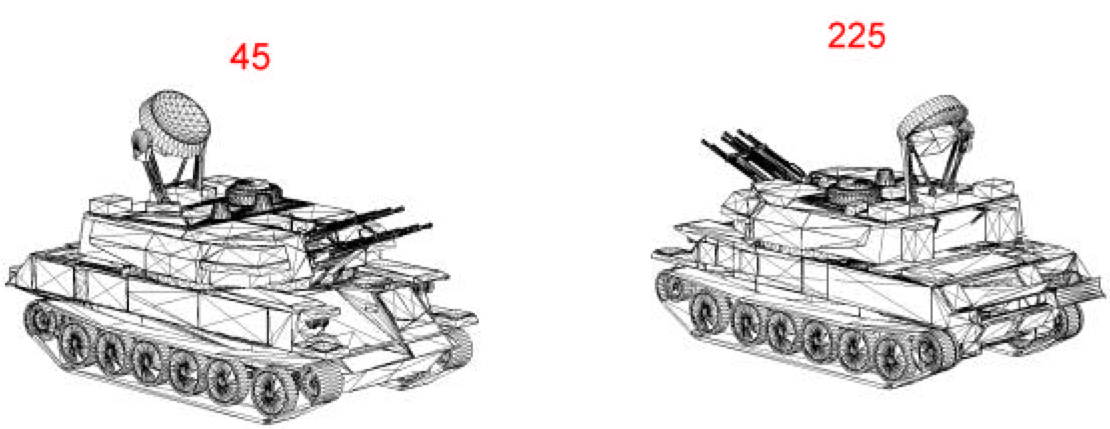

Figure 4. “ModelMan” software (from SAIC), showing ZSU-23-4 over metal ground plane (plane size = 2200 in.).

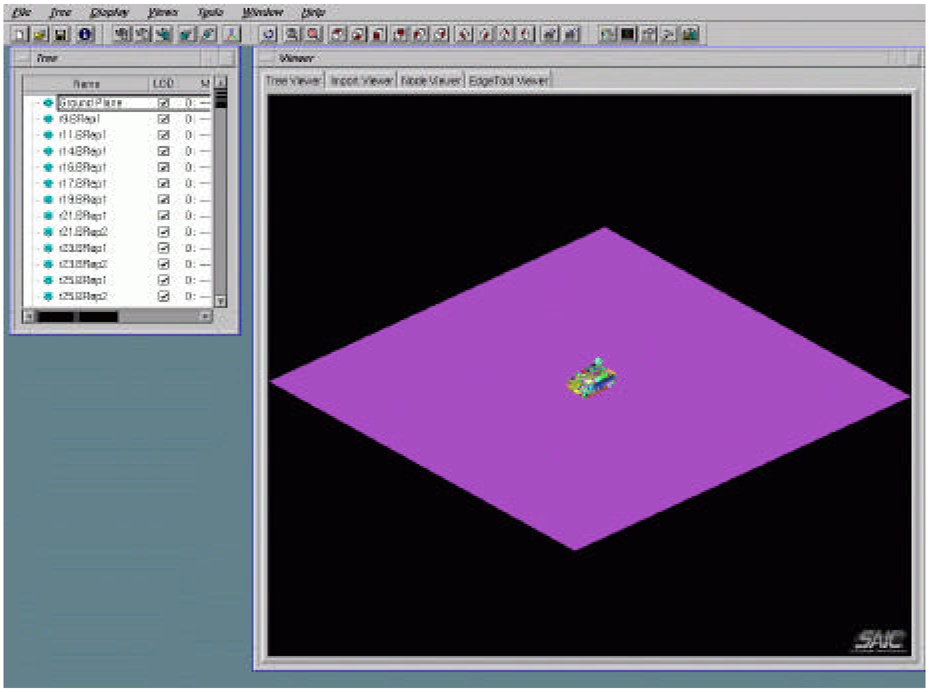

Figure 5. Comparison of Xpatch and APG RCS data for ZSU measurement at K_a-band, 30° elevation angle, copolarized field components (vertical transmit, vertical receive).

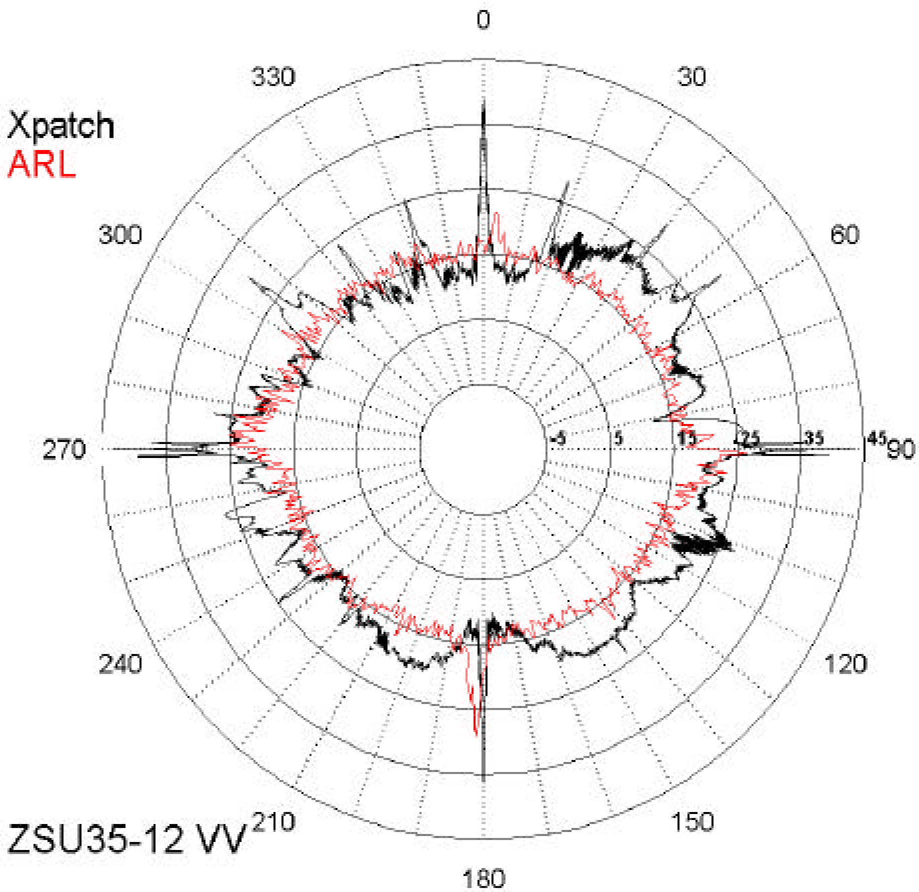

Figure 6. Comparison of Xpatch and APG ISAR data for ZSU measurements at *X*-band, 30° elevation angle, −135° azimuth angle.

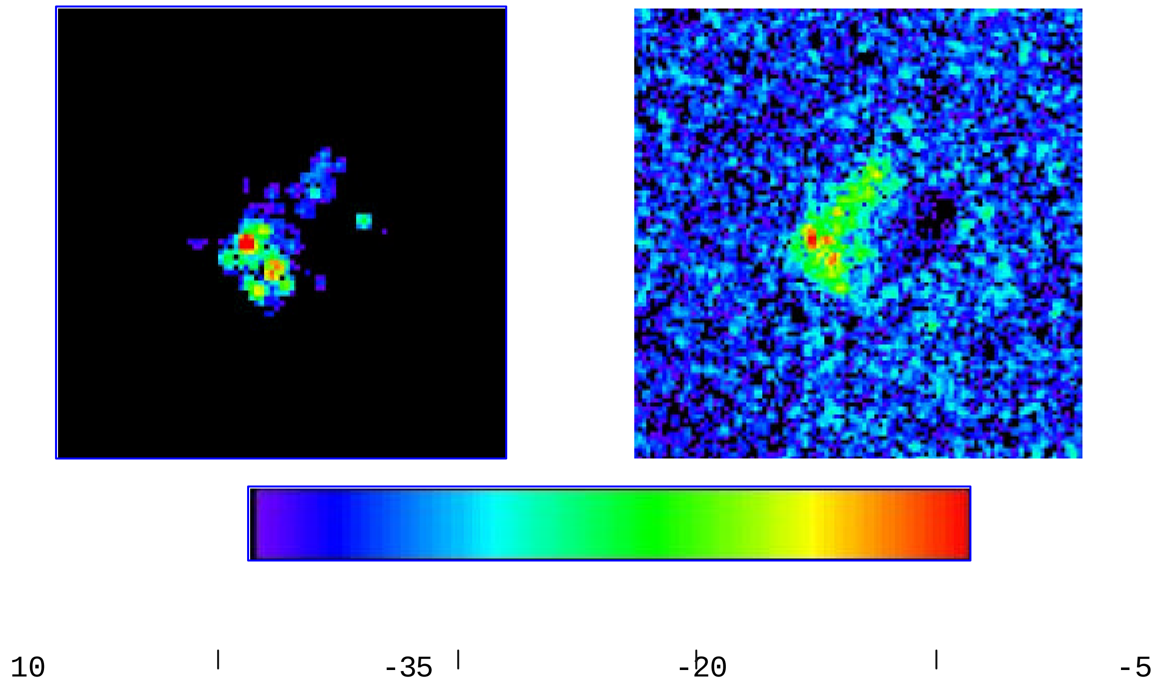

Figure 7. ZSU high-fidelity virtual target model (from TMO) containing 852,803 facets.